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Canadian Association of Radiologists Journal 63 (2012) 260−266

CANADIAN ASSOCIATION OF RADIOLOGISTS JOURNAL

www.carjonline.org

Computed Tomography / Tomodensitométrie

The Relationship of Body Mass Index and Abdominal Fat on the Radiation Dose Received During Routine Computed Tomographic Imaging of the Abdomen and Pelvis

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Abstract

Purpose: To determine the relationship of increasing body mass index (BMI) and abdominal fat on the effective dose acquired from computed tomography (CT) abdomen and pelvis scans.
Methods: Over 6 months, dose-length product and total milliamp-seconds (mAs) from routine CT abdomen and pelvis scans of 100 patients were recorded. The scans were performed on a 64-slice CT scanner by using an automatic exposure control system. Effective dose (mSv) based on dose-length product, BMI, periumbilical fat thickness, and intra-abdominal fat were documented for each patient. BMI, periumbilical fat thickness, and intra-abdominal fat were compared with effective dose.
Results: Thirty-nine men and 61 women were included in the study (mean age, 56.3 years). The mean BMI was 26.2 kg/m^2. The mean effective dose was 10.3 mSv. The mean periumbilical fat thickness was 2.4 cm. Sixty-five patients had a small amount of intra-abdominal fat, and 35 had a large amount of intra-abdominal fat. The effective dose increased with increasing BMI ($P < .001$) and increasing amounts of intra-abdominal fat ($P < .001$). For every kilogram of weight, there is a 0.13 mSv increase in effective dose, which is equal to 6.5 chest radiographs per CT examination. For an increase in BMI by 5 kg/m^2, there is a 1.95 mSv increase in effective dose, which is equal to 97.5 chest radiographs per CT examination.
Conclusion: Increasing BMI and abdominal fat significantly increases the effective dose received from CT abdomen and pelvis scans.

Résumé

Objectif : Déterminer l'incidence de l'accroissement de l'indice de masse corporel (IMC) et de l'adiposité abdominale sur la dose efficace reçue au cours d'une tomodensitométrie de l'abdomen et du bassin.
Méthodes : Sur une période de six mois, le produit dose-longueur (PDL) et les milliampères-secondes (mAs) totaux reçus pour une tomodensitométrie (TDM) de routine de l'abdomen et du bassin réalisée sur 100 patients ont été enregistrés. Les TDM ont été effectuées à l'aide d'un tomodensitomètre muni de 64 barrettes et d'un dispositif de commande automatique d'exposition. La dose efficace (mSv), fondée sur le produit dose-longueur, l'IMC, la couche adipeuse de la région périombilicale et l'adiposité intra-abdominale a été documentée pour chaque patient. L'IMC, la couche adipeuse de la région périombilicale et l'adiposité intra-abdominale ont été comparés avec la dose efficace.
Résultats : Cette étude a porté sur 39 hommes et 61 femmes (âge moyen de 56,3 ans). L'IMC moyen était de 26,2 kg/m2. La dose efficace moyenne était de 10,3 mSv. La couche adipeuse moyenne de la région périombilicale était de 2,4 cm. Soixante-cinq patients avaient une faible adiposité intra-abdominale et 35 patients avaient une adiposité intra-abdominale élevée. La dose efficace augmentait en fonction de la hausse de l'IMC ($P < .001$) et de l'augmentation de l'adiposité intra-abdominale ($P < .001$). Pour chaque kilogramme supplémentaire, la dose efficace augmente de 0,13 mSv, ce qui correspond à la dose de 6,5 radiographies pulmonaires par TDM. Une hausse de 5 kg/m2 de l'IMC correspond à une augmentation de 1,95 mSv de la dose efficace, ce qui équivaut à 97,5 radiographies pulmonaires par TDM.

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doi:10.1016/j.carj.2011.02.006

Conclusion : Une hausse significative de l'IMC et de l'adiposité abdominale entraîne une majoration considérable de la dose efficace reçue au cours d'une tomodensitométrie de l'abdomen et du bassin.

Key Words: Radiation dose; Computed tomography; Abdomen; Body mass index

Medical imaging results in the largest exposure to ionizing radiation from non-natural sources. The use of ionizing radiation in medical imaging is governed by the ALARA principle which states that necessary diagnostic information of clinically satisfactory quality should be obtained at a dose that is "as low as reasonably achievable" [1]. However, there is growing concern over the radiation dose to patients from computed tomography (CT) studies. Although CT represents approximately 10% of the x-ray−based examinations, it accounts for almost 50% of the collective radiation dose associated with medical imaging [2]. For example, the annual dose from natural background radiation is 3 mSv, the dose from a chest radiograph is 0.02 mSv and that of a CT abdomen and pelvis scan is 10 mSv (slightly lower in the United Kingdom) (Tables 1 and 2) [2,3], which stems from the rapidly increasing availability of CT and the advent of multidetector row CT (MDCT), which, in turn, has increased patient volumes and enhanced clinical applications. Total doses for repeated examinations are correspondingly higher.

There are recent articles of studies that focused on the estimated risk of cancer development due to the use of diagnostic x-ray procedures. Gonzalez and Darby [4] reported that the estimated risk of cancer from all diagnostic x-ray procedures is between 0.6% and 3.2% of that for all cancers in the developed countries. Indeed, the current risks are likely higher because the data used in this study were taken from 1991-1996. The radiation doses of CT examinations, therefore, can approach and sometimes exceed levels that may increase the probability of cancer and add to the lifetime cancer mortality risk of the natural background cancer rate [5].

The quantity most relevant for assessing risk of cancer from CT is the "effective dose." Effective dose (Ef) is the weighted sum of the doses to all irradiated organs, with the weighting incorporating the different radiosensitivities of the various organs in the body [1,2]. The Ef allows the comparison of the risk estimates associated with partial- or whole-body radiation exposures. The Ef from any given CT study depends on a number of factors, including the design of the CT scanner, tube current and scanning time in mAs, axial scan range, and patient size. Patient size plays an important role, because thicker tissues attenuate more x-rays and produce more scatter. To counteract this process, higher tube currents are required to reduce noise and maintain image quality, which subsequently increases the radiation dose to the patient.

Various strategies have been recommended to reduce the radiation dose to the patient in CT imaging. In 1998, online attenuation-based automatic tube current modulation was introduced [6]. It is based on the principle that x-ray attenuation and quantum image noise are determined by the size of the object and its tissue density. One method of automatic tube current modulation is the angular, or *xy*-axes modulation, which decreases the tube current in projections (in the *xy* plane) with relatively low attenuation (ie, anteroposterior vs lateral). Another method is the *z*-axis modulation, which automatically selects a tube current for each slice position in the scanning direction (ie, shoulders vs abdomen vs pelvis). The combined, or *xyz*-axes, automatic tube current modulation merges the complementary techniques of angular and *z*-axis modulation to yield an added reduction in radiation dose for the same level of image quality compared with either angular or *z*-axis modulation alone [7]. This automatic exposure control (AEC) system provides a substantial reduction in radiation dose, with equal or even improved image quality [8].

However, there is a potential risk of very high radiation doses to oversized patients when an AEC system is used, because imaging of patients who are obese is often complicated by scatter and relative increase in image noise at routine radiation doses. Because it is clinically desirable to maintain image quality over a range of patient sizes, many

Table 1
Radiation dose comparison (US Food and Drug Administration) [3]

Diagnostic procedure	Typical effective dose (mSv)	No. chest radiographs (PA film) for equivalent effective dose[a]	Time period for equivalent dose from natural background radiation[b]
Chest radiograph (PA film)	0.02	1	2.4 d
Skull radiograph	0.07	4	8.5 d
Lumbar spine	1.3	65	158 d
Intravenous urogram	2.5	125	304 d
Upper gastrointestinal examination	3.0	150	1.0 d
Barium enema	7.0	350	2.3 y
CT head	2.0	100	243 d
CT abdomen	10.0	500	3.3 y

CT = computed tomography; PA = posterioanterior.
[a] Based on the assumption of an average effective dose of 0.02 mSv.
[b] Based on the assumption of an average effective dose of 3 mSv/y.

Table 2
Typical adult doses from CT in the United Kingdom (2003 review) [2]

CT examination	DLP (mGy.cm)[a]	Effective dose (mSv)
Head	690	1.5
Abdomen	350	5.3
Abdomen and pelvis	470	7.1
Chest, abdomen, and pelvis	670	9.9
Chest	400	5.8
High-resolution chest	88	1.2

CT = computed tomography; DLP = dose-length product.
[a] For examinations of the head, calculated values of DLP relate to the 16-cm-diameter CT dosimetry phantom; for examinations of the trunk, calculated values of DLP relate to the 32-cm-diameter CT dosimetry phantom.

Table 3
The 64-Slice multidetector row computed tomography protocol for a routine abdomen and pelvis examination

Reference source	ctisus.com, Siemans Application Guide
Scanner	Siemans Sensation 64
kV/effective mAs/rotation time (s)	120/250/0.5
Detector collimation (mm)	0.6
Pitch	1.15
Scan direction	Craniocaudal
Scan range	From diaphragm to symphysis pubis
Oral contrast	1 L gastrografin 2.5%, 1 h before scan
Intravenous contrast	100 mL Ultravist 300 (Bayer Schering Pharma, Berlin-Wedding, Germany)
Injection rate	2 mL/s
Scan delay (s)	60

radiologists are tempted to use a constant operator-selected image-quality setting (eg, noise index, reference tube current-time product) [9] but at the expense of radiation dose to the patient. Thus, patient size is an important consideration in CT acquisitions performed with an AEC system.

Therefore, the purpose of our study was to determine the relationship of both increasing body mass as well as the amount of abdominal fat on the Ef acquired from a routine CT of the abdomen and pelvis performed with a 64-slice MDCT scanner using an AEC system.

Patients and Methods

This was a prospective study from September 2007 to February 2008 in which 100 patients already scheduled for a CT abdomen and pelvis scan for various clinical indications were weighed and heights were measured before the examination. Approval by our local research ethics committee was not required because the patients were already scheduled for a CT and were not subjected to an additional unnecessary scan. Furthermore, no clinical details were taken from the patients' medical notes. However, informed oral consent to participate in the study was obtained from each patient before his or her scan. The body mass index (BMI) (kg/m^2) was then calculated from the weight (kg) and height (m).

The CT examinations were performed by using a 64-slice MDCT scanner (Somatom Sensation Cardiac 64; Siemens, Erlangen, Germany). A standard imaging protocol was used (Table 3). Tube current was controlled by the software package CARE Dose 4D (Siemens), which uses a combined angular and z-axis modulation technique. This AEC system modulates the tube current within the section (angular) as well as within different anatomic regions (z-axis). It uses automatic tube-current adaptation to the patient's size and anatomic shape, together with an on-line controlled tube-current modulation for each tube rotation. Based on a single anteroposterior or lateral topogram, CARE Dose 4D determines the adequate tube current level (mAs) for each section of the patient and modulates the tube current to maintain similar image quality throughout the scan length. Therefore, the scan length and dose are specific for each patient. It provides a well-balanced image quality at lower radiation dose levels. The software package then generates the dose-length product (DLP) (mGy.cm) and total mAs for each examination, which, again, is specific for each patient. DLP is a measure of the total radiation exposure for the whole series of images. An Ef (mSv) was then calculated by multiplying the DLP by a normalized value of Ef (k) per DLP for an adult CT abdomen and pelvis scan (Table 4) [1,2,10,11].

$$\mathrm{Ef} = k * \mathrm{DLP}$$

From the CT examinations, periumbilical fat thickness (cm) within 2 cm of the umbilicus was measured. Qualitative analysis of the amount of intra-abdominal fat (small or large) at the umbilical level based on the degree of fat deposition around the abdominal organs was performed for each patient by 2 blinded radiologists independently. Interobserver variability (kappa score) was calculated for the qualitative analysis, and any disagreements were resolved by consensus. Ef was compared with BMI, periumbilical fat thickness, and amount of intra-abdominal fat. BMI and amount of intra-abdominal fat compared with Ef were further analysed based on sex. BMI was also compared with total mAs.

Statistical analysis was performed with commercially available statistical software (Epi Info Version 3.5; Centers for Disease Control and Prevention, Atlanta, GA). A P value of less than .05 was used to indicate a statistically significant difference.

Results

Over the 6-month period, 39 men and 61 women (n = 100) were recruited into the study. Their ages ranged from 17-91 years (mean, 56.3 years). BMI ranged from 16.7-44.3 kg/m^2 (mean [SD], 26.2 [$\pm$ 5.9] kg/m^2). The mean (SD) BMI

Table 4
Normalized values of effective dose per DLP over various body regions for a standard adult [2]

Region of body	Effective dose per DLP (mSv/mGy.cm)
Head and neck	0.0031
Head	0.0021
Neck	0.0059
Chest	0.014
Abdomen and pelvis	0.015
Trunk	0.015

DLP = dose-length product.

in the men was 26.1 ($\pm$ 6.6) kg/m^2 and that in the women was 26.2 ($\pm$ 4.5) kg/m^2, with no statistically significant difference (P = .95). Thirteen patients had a low BMI (<20 kg/m^2), 34 patients had a normal BMI (20-24.9 kg/m^2), and 51 patients had a high BMI (>25 kg/m^2). The Ef ranged from 6-24 mSv (mean [SD], 10.3 [$\pm$ 2.8] mSv). The mean (SD) Ef in the men was 10.5 ($\pm$ 2.3) mSv and in women was 10.1 ($\pm$ 3.1) mSv, with no statistically significant difference (P = .58). Periumbilical fat thickness ranged from 0.3-6.3 cm (mean [SD] 2.4 [$\pm$ 1.1]). The mean (SD) periumbilical fat thickness for the men was 2.2 ($\pm$ 0.9) and for the women was 2.5 ($\pm$ 1.1), with no statistically significant difference (P = .19). Sixty-five of the patients had a small amount of intra-abdominal fat (Figure 1), and 35 had a large amount of intra-abdominal fat (Figure 2), with a kappa score of 0.73. The majority of the men had a large amount of intra-abdominal fat (20/39 [51%]), whereas, the majority of the women had a small amount of intra-abdominal fat (46/61 [75%]).

A comparison of Ef to BMI showed that the Ef increased with increasing BMI, $P < .001$ (Figure 3). This relationship held true for the men and women separately. Similar results were obtained when total mAs was compared with BMI, $P < .001$ (Figure 4). The mean (SD) Ef for a low BMI was 7.3 ($\pm$ 0.9) mSv, for a normal BMI was 8.9 ($\pm$1.0) mSv, and for a high BMI was 12.0 ($\pm$ 2.8) mSv, with a statistically significant difference ($P < .001$). For the men, the mean (SD) Ef for a low BMI was 6.4 ($\pm$ 0.7) mSv, a normal BMI was 9.2 ($\pm$ 0.7) mSv, and a high BMI was 11.8 ($\pm$ 2.0) mSv, with a statistically significant difference ($P < .001$). For the women, the mean (SD) Ef for a low BMI was 7.6 ($\pm$ 0.7) mSv, for a normal BMI was 8.6 ($\pm$ 1.1) mSv, and for a high BMI was 12.2 ($\pm$ 3.3) mSv, with a statistically significant difference ($P < .001$).

Increasing periumbilical fat thickness was also associated with an increased Ef, $P < .001$ (Figure 5). The majority of the patients with a small amount of intra-abdominal fat had an Ef that was lower than the average Ef for a CT abdomen and pelvis scan (ie, <10 mSv) (Figure 6), whereas the majority of the patients with a large amount of intra-abdominal fat had an Ef that was higher than the average Ef for a CT abdomen and pelvis scan (ie, >10 mSv) (Figure 7).

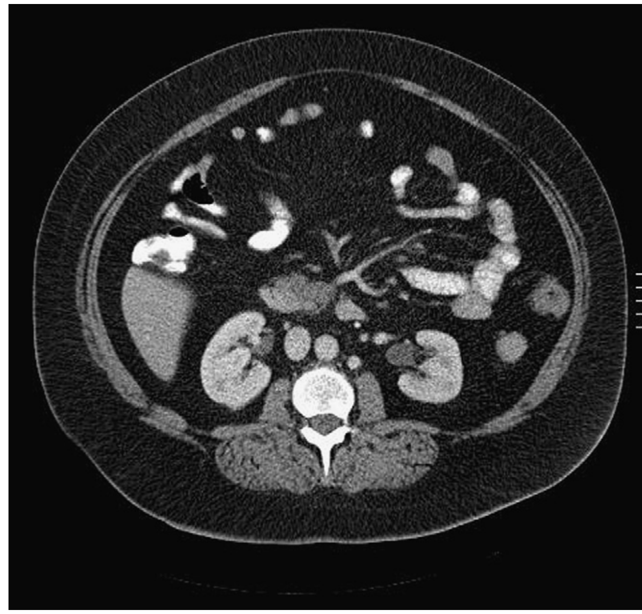

Figure 2. An example of a patient with a “large” amount of intra-abdominal fat.

Figure 1. An example of a patient with a “small” amount of intra-abdominal fat.

Discussion

With the evolution of CT scanners, concerns regarding the increasing radiation doses associated with CT scanning have emerged. Wall and Hart [12] reported an increase in radiation doses of about 35% for a CT of abdomen and pelvis over the past 10 years. Inherent to the design, MDCT results in a higher radiation dose than single-detector row CT. Thomton et al [13] showed that MDCT had a 27% higher dose profile than single-detector row CT in the imaging plane and a 69% higher dose profile than single-detector row CT adjacent to the imaging plane.

AEC systems for MDCT scanners are now available from all major scanner manufacturers under different names. These dose modulation systems operate in a variety of ways, but their main purpose is to adjust radiation dose according to the patient’s attenuation and ultimately reduce the radiation dose to the patient while maintaining diagnostic image

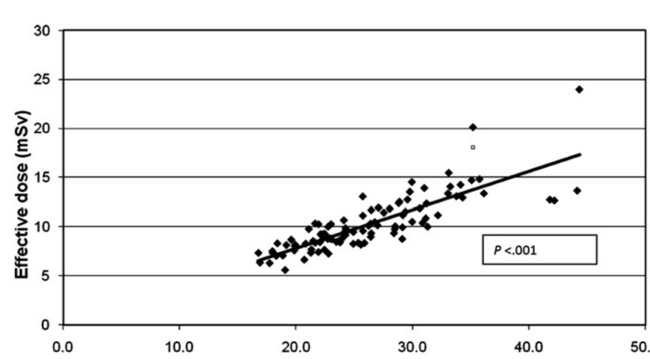

Figure 3. A comparison of body mass index (BMI) and effective dose.

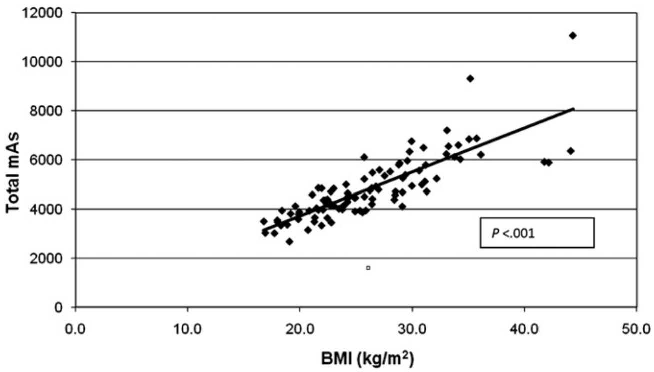

Figure 4. Comparison of body mass index (BMI) and total mAs.

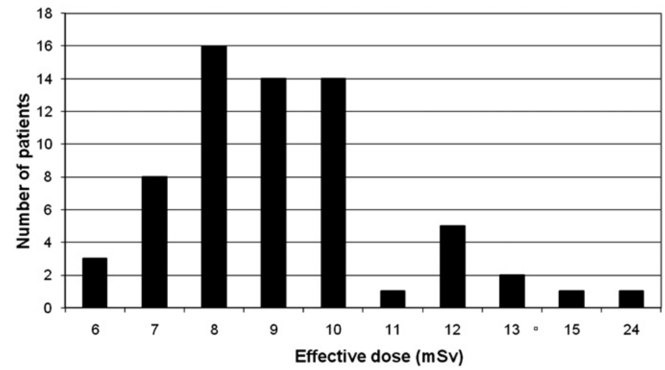

Figure 6. The number of patients with a small amount of intra-abdominal fat who received a particular effective dose.

quality [14]. Researchers have reported an average reduction in tube current-time product of up to 38% with less image noise in 75% of CT studies, better low-contrast detectability in 51%, and superior overall image quality in 71% compared with images acquired with fixed tube current protocols [15]. Another study subsequently showed a 15%-60% tube current-time product reduction when using angular modulation in scanning 6 anatomic regions [16].

Although the aim of automated tube current modulation is to reduce the overall radiation dose while maintaining image quality, the potential risk of very high radiation doses to patients who are oversized has been reported in several studies [5,17,18], because there is greater beam attenuation with thicker tissues, which results in greater noise and which will require higher tube current to maintain constant image quality. Schindera et al [9] demonstrated in a phantom study adjusted for 3 patient sizes that abdominal organ doses for the larger patient increased by 426.9%-528.1% compared with the smaller patient undergoing abdominal CT with automatic tube current modulation. A recent study found that, for body CT examinations performed with an AEC system, the radiation used in patients who weighs 100 kg is approximately 3 times that for a patient who weighs 60 kg, and results in organ doses that are generally twice as high as those in a patient who weighs 60 kg [19].

Our study has illustrated that an increased BMI was associated with an increased radiation dose acquired from an abdominal MDCT using an AEC system. For every kilogram of weight, there was a 0.13 mSv increase in Ef, which is equal to 6.5 chest radiographs per CT examination. For an increase in BMI by 5 kg/m^2, there was a 1.95 mSv increase in Ef, which is equal to 97.5 chest radiographs per CT examination. Although the reasons for this are likely multifactorial, we have shown that both periumbilical fat thickness and the amount of intra-abdominal fat have a significant effect on radiation dose. There was no significant difference between men and women. However, men tended to have larger amounts of intra-abdominal fat, which was associated with a higher dose.

A limitation of the study was the method of estimating the Ef from the scanner displayed DLP. Although it has been proven to be a reliable method within 10%-15%, the normalized value of Ef per DLP for an adult CT abdomen and pelvis scan refers to a standard physique (70 kg), with a body diameter and composition that is fairly well represented by a 32-cm-diameter acrylic body phantom. Changes in the scanner displayed DLP (for the same scanned length) due to changes in the mAs also refer to a 32-cm-diameter acrylic phantom. If the size and composition of the patient deviated significantly from the standard physique, then the DLP, normalized value of Ef per DLP, and, therefore, the Ef would become unreliable. However, tube current (mAs) varies with tissue thickness regardless of overall body shape, and our study demonstrated that total mAs also increased with increasing BMI ($P < .001$). It should be noted though, as stated

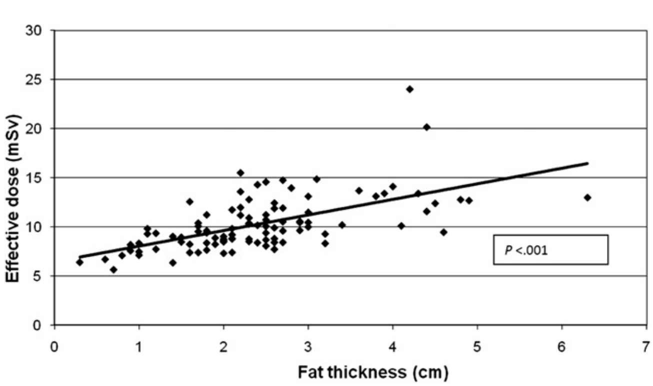

Figure 5. Comparison of periumbilical fat thickness and effective dose.

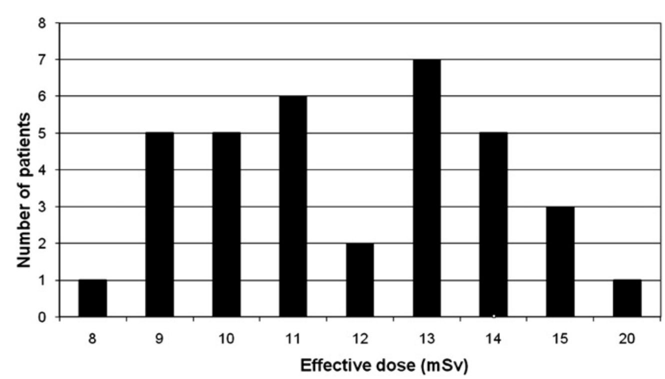

Figure 7. The number of patients with a large amount of intra-abdominal fat who received a particular effective dose.

by the United Nations Scientific Committee on the Effects of Atomic Radiation, that the Efs should not be used directly for estimating detriment (to individuals or populations) from medical exposure; the analysis of radiation risk from diagnostic medical exposure requires detailed knowledge of organ doses and the age and sex of the patients [20]. The International Commission on Radiological Protection (ICRP) report [1] also stresses that Ef is intended only as a protection quantity and not for epidemiologic evaluations.

As far as we know, there are no dose limits for patients as such, but the use of x-rays in diagnostic imaging is governed by the ALARA principle. DRLs have been established to promote improvements in the optimization of radiation protection for patients. The national reference dose for a CT abdomen and pelvis examination, as reported by Shrimpton et al [2] in 2003 is 560 mGy.cm. In our study, the DLP ranged from 374-1598 mGy.cm (mean, 685 mGy.cm). Of the 51 patients with a high BMI (>25 kg/m^2), only 3 had a DLP below the DRL, which is of great concern, because DLP is directly related to the patient (stochastic) risk. Because obesity is a major problem worldwide, with a prevalence that continues to rise, this increase in radiation dose poses a potential increase in the risk of stochastic effects.

Stochastic effects are caused by damage to cells that produce genetically transformed but reproductively viable descendents. Cancer and genetic effects of radiation are considered to be stochastic. The stochastic effect is seen even at low doses, and its probability increases linearly with dose. There is no threshold dose for stochastic effects. Therefore, even the smallest dose has the potential to cause a small increase in cancer risk to humans.

The relationship of these radiation exposures to biologic risk for patients is determined by mathematical extrapolation based on changes observed after exposure to much higher levels of radiation. In a recent report on cancer incidence in survivors of the atomic bomb, individuals in the dose category from 5-100 mSv (mean, 29 mSv) showed a statistically significant increase in solid cancer risk [21].

Such estimates of the cancer risk from x-ray exposure have a broad range of statistical uncertainty, and the scientific community remains divided regarding the radiation dose effects of CT. In reality, CT should be used judiciously and only when medically indicated to keep patient radiation exposures from CT as low as possible [22]. Alternative imaging methods, such as ultrasonography or magnetic resonance imaging, should be considered. Once the CT examination is justified, a CT protocol should be applied to provide the optimal image quality with the lowest possible radiation dose [11]. For example, there are specific clinical indications in which high contrast lesions are surrounded by low contrast structures such as in renal calculus evaluation, CT colonography, and CT pulmonary angiography. In these cases, dedicated low-dose protocols have been used to minimize radiation dose [23]. Other CT protocols that aim to reduce the radiation dose to patients have also been published [24,25]. Silva et al [23] recently demonstrated a new method for noise reduction based on iterative reconstruction algorithms that is able to correct image data when using a system of models. They reported that using this method of image reconstruction allows for image noise reduction and improved image quality in CT examinations performed on patients who are obese, including standard low-dose CT protocols and even ultra-low-dose techniques.

Finally, with no set standard, CT scanner manufacturers have created their own ways of modulating radiation dose, thereby creating the need for both the radiologist and radiographer to understand how to use different AEC systems [14,26−28]. Appropriate AEC parameters, for example, noise index, have to be selected for each patient-size group [7,9]. Industry standards organizations need to build a consensus so that a more uniform automatic tube-current modulation technique is offered to the user to minimize confusion and ensure appropriate use of the technique [26].

Conclusion

There is no doubt that the medical information derived from appropriate diagnostic CT examinations saves lives. Although the consequences of the radiation exposure from CT remain subject to interpretation of the sparse data that are available, our study has shown that the radiation dose from an abdominal CT for patients who are obese is significantly higher than that for the smaller patient. AEC in CT is a very useful tool for dose optimization, but dose savings are not guaranteed unless the technique is used properly. Protocols should be designed carefully, according to each system's capability, patient size, and clinical indication for the scan. Because obesity continues to be growing public health concern and CT increasingly plays an important role in the diagnostic evaluation of patients who are obese and with abdominal comorbidities, more data are needed to solve this clinical conundrum.

References

[1] ICRP. ICRP Publication 60. 1990 Recommendations of the International Commission on Radiological Protection, 60. Oxford (UK): Pergamon; 1991.

[2] Shrimpton PC, Hillier MC, Lewis MA, et al. Doses from computed tomography examinations in the UK: 2003 review. Report NRPB-W67. Chilton (UK): NRPB; 2004.

[3] US Food and Drug Administration/Center for Devices and Radiological Health. 2008. Whole body scanning: what are the radiation risks from CT? Available at: http://www.fda.gov/cdrh/ct/risks.html. Accessed July 14, 2008.

[4] Gonzalez AB, Darby S. Risk of cancer from diagnostic x-rays: estimates for the UK and 14 other countries. Lancet 2004;363:345−51.

[5] Mulkens MD, Bellinck P, Baeyaert M, et al. Use of an automatic exposure control mechanism for dose optimization in multi-detector row CT examinations: clinical evaluation. Radiology 2005;237:213−23.

[6] Rizzo S, Kalra M, Schmidt B, et al. Comparison of angular and combined automatic tube current modulation techniques with constant tube current CT of the abdomen and pelvis. AJR Am J Roentgenol 2006;186:673−9.

[7] Gudjonsdottir J, Borgny W, Olsen DR. Optimal use of AEC in CT: a literature review. Radiol Technol 2010;81:309−17.

[8] Tack D, De Maetelaer V, Gevenois PA. Dose reduction in multidetector CT using attenuation-based online tube current modulation. AJR Am J Roentgenol 2003;181:331−4.
[9] Schindera ST, Nelson RC, Toth TL, et al. Effect of patient size on radiation dose for abdominal MDCT with automatic tube current modulation: phantom study. AJR Am J Roentgenol 2008;190:W100−5.
[10] Huda W, Ogden KM, Khorasani MR. Converting dose-length product to effective dose at CT. Radiology 2008;248:995−1003.
[11] Tsapaki V, Rehani M, Saini S. Radiation safety in abdominal computed tomography. Semin Ultrasound CT MR 2010;31:29−38.
[12] Wall BF, Hart D. Revised radiation doses for typical x-ray examinations, report on a recent review of doses to patients from medical x-ray examinations in the UK by NRPB. Br J Radiol 1997;70:437−9.
[13] Thomton FJ, Paulson EK, Yoshizumi TT, et al. Single versus multidetector row CT: comparison of radiation doses and dose profiles. Acad Radiol 2003;10:379−85.
[14] Lee CH, Goo JM, Ye HJ, et al. Radiation dose modulation techniques in the multidetector CT era: from basics to practice. Radiographics 2008;28:1451−9.
[15] Greess H, Wolf H, Baum U, et al. Dosage reduction in computed tomography by anatomy-oriented attenuation-based tube-current modulation: the first clinical results. Rofo 1999;170:246−50.
[16] Greess H, Wolf H, Baum U, et al. Dose reduction in computed tomography by attenuation-based on-line modulation of tube current: evaluation of six anatomical regions. Eur Radiol 2000;10:391−4.
[17] Kalra MK, Maher MM, Toth TL, et al. Comparison of Z-axis automatic tube current modulation technique with fixed tube current CT scanning of abdomen and pelvis. Radiology 2004;232:347−53.
[18] McCollough CH, Bruesewitz MR, Kofler Jr JM. CT dose reduction and dose management tools: overview of available options. Radiographics 2006;26:503−12.
[19] Israel GM, Cicchiello L, Brink J, et al. Patient size and radiation exposure in thoracic, pelvic, and abdominal CT examinations performed with automatic exposure control. AJR Am J Roentgenol 2010;195:1342−6.
[20] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): Sources and effects of ionizing radiation: report to the general assembly, with scientific annexes. New York: United Nations; 2000.
[21] Brenner DJ, Elliston CD. Estimated radiation risks potentially associated with full-body CT screening. Radiology 2004;232:735−8.
[22] Birnbaum S. Radiation protection in the era of helical CT: practical patient based programs for decreasing patient exposure. Semin Ultrasound CT MR 2010;31:46−52.
[23] Silva AC, Lawder HJ, Hara A, et al. Innovations in CT dose reduction strategy: application of the adaptive statistical iterative reconstruction algorithm. AJR Am J Roentgenol 2010;194:191−9.
[24] Nakayama Y, Awai K, Funama Y, et al. Abdominal CT with low tube voltage: preliminary observations about radiation dose, contrast enhancement, image quality, and noise. Radiology 2005;237:945−51.
[25] Schindera ST, Nelson RC, Lee ER, et al. Abdominal multislice CT for obese patients: effect on image quality and radiation dose in a phantom study. Acad Radiol 2007;14:486−94.
[26] Kalra MK, Maher MM, Toth TL, et al. Techniques and applications of automatic tube current modulation for CT. Radiology 2004;233:649−57.
[27] Söderberg M, Gunnarsson M. Automatic exposure control in computed tomography: an evaluation of systems from different manufacturers. Acta Radiol 2010;51:625−34.
[28] Valentin J. Managing patient dose in multi-detector computed tomography (MDCT). ICRP Publication 102. Ann ICRP 2007;37:1−79, iii.